Status and prospects of the NA62 experiment

Chris Parkinson, University of Birmingham

27th January 2016
1. Flavour physics in the 21st century and the NA62 experiment

2. The NA62 experimental setup

3. Detector commissioning and data-taking in 2014 and 2015

4. The NA62 physics programme and proposed trigger strategy
Plenty of unanswered questions

Dark Matter

Neutrino properties

Lack of CPV

New particles at the TeV scale
Searching for new particles

- New particles can contribute to loop-mediated processes
- In the Standard Model, FCNC decays are forbidden at tree level → loop diagrams

Example: $B^0$ mixing

\[ M(B_d - \bar{B}_d) \sim \frac{(y_t^2 V_{tb} V_{td})^2}{16\pi^2 m_t^2} \]

- FCNC decays are highly suppressed:
  - Because they are \textit{forbidden at tree level}
  - Because the \textit{off-diagonal CKM elements are small}
  - Because of the \textit{GIM mechanism}
New particles can contribute to loop-mediated processes

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- Because of the GIM mechanism

$C_{NP} \sim O(1)$
The flavour problem

- But we don’t see huge NP contributions to FCNC decays?
  \[
  C_{NP} \frac{1}{\Lambda^2} \ll \text{SM term}
  \]

- Either:
  - New particles are extremely massive \((\Lambda \to \infty)\).
  - The couplings of the new particle are suppressed too \((C_{NP} \ll 1)\).
Complementarity

- The fact that $C_{NP} \frac{1}{\Lambda^2} \ll \text{SM term}$ sets $C_{NP}$-dependent limits on $\Lambda$
- This provides great complementarity with direct searches for new particles

[Straub, IPPP 2014]
Experimentally we measure \( \sim \) the sum of both terms.

But we can predict the SM-only value.

Any difference is due to a NP contribution.

If there is no difference, this sets limits on the size of NP contributions.
Three criteria for searches

- Searching for new particles in this way

needs three criteria to be satisfied:

1. SM contribution must be small
2. Precise calculation of SM contribution
3. Experimentally accessible observable

- These criteria are satisfied by the FCNC decay $K^+ \rightarrow \pi^+ \nu \nu$
The $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ decay

- Small and precisely determined SM contribution
  \[ B(K^+ \rightarrow \pi^+ \nu \bar{\nu}) = (9.11 \pm 0.72) \times 10^{-11} \]  
  - Highly suppressed due to ‘hard-GIM’ suppression

- Experimentally accessible?
  - Actually this is quite difficult. Require a specialised experiment $\rightarrow$ NA62
Current experimental status of $K^+\to\pi^+\nu\bar{\nu}$

- Combined data from E787 and E949 experiments @ BNL
- Use ‘stopped Kaon’ approach to detect $K^+$ decays at rest
- Based on $9.4\times10^{12}$ $K^+$ decays – collected seven signal candidates

Prediction \cite{Buras et al.}:

$$\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu}) = (9.11 \pm 0.72) \times 10^{-11}$$

- Measured $\mathcal{B}(K^+\to\pi^+\nu\bar{\nu})$ to be

$$\text{BR}(K^+ \to \pi^+\nu\bar{\nu}) = (1.73^{+1.15}_{-1.05}) \times 10^{-10}$$

\text{BNL E787/E949: PRL101 (2008) 191802}

- The ‘excess’ could be evidence of contributions from $Z'$


- Similar interpretation to recent LHCb results
The impact of $K^+ \rightarrow \pi^+ \nu \bar{\nu}$

[Straub, CKM2010]
The impact of $K^+ \rightarrow \pi^+ \nu\bar{\nu}$

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The impact of $K^+ \rightarrow \pi^+ \nu \bar{\nu}$

[Diagram showing the impact of $K^+ \rightarrow \pi^+ \nu \bar{\nu}$]

10% measurement

[Buras et. al. 2012]
The NA62 experiment
The NA62 collaboration
**Recent history of NA experiments**

<table>
<thead>
<tr>
<th>Year</th>
<th>Experiment</th>
<th>Description</th>
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<tbody>
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<td>1984-1990</td>
<td>NA31 ($K_S/K_L$)</td>
<td>First evidence of direct CPV</td>
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<td>$\text{Re } \varepsilon'/\varepsilon$ Discovery of direct CPV</td>
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<td>2002</td>
<td>NA48/1 ($K_S$/hyperons)</td>
<td>Rare $K_S$ and hyperon decays</td>
</tr>
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<td>2003-2004</td>
<td>NA48/2 ($K^+$/K$^-$)</td>
<td>Direct CPV Rare $K^+$ / K$^-$ decays</td>
</tr>
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<td>2007-2008</td>
<td>NA62 $R_K$ phase ($K^+$/K$^-$)</td>
<td>$R_K = K^+<em>{e\nu}/K^+</em>{\mu\nu}$</td>
</tr>
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<td>2009-2017</td>
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<td>$K^+ \rightarrow \pi^+ \nu\nu$ Rare $K^+$ and $\pi^0$ decays</td>
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**NA62**: 233 collaborators of 29 institutes
## Recent history of NA experiments

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Some results later!
Requirements of the NA62 experiment

- NA62 aims to make a 10% branching fraction measurement, to match the precision of the theory calculation
  - Must collect at least 100 signal events

- Assume SM branching fraction $\rightarrow 9.11 \times 10^{-11}$ (let's say $10^{-10}$)
- Assume (realistic) 10% signal acceptance

- To collect 100 events:
  \[
  100 / (0.1 \times 10^{-10}) = 10^{13} \text{ } K^+ \text{ decays in fiducial volume}
  \]

- For every 100 signal events, must have less than 10 background events ... 
  Background rejection at the level of $10^{-12}$

- Measuring $K^+ \rightarrow \pi^+ \nu \nu$ needs a huge Kaon rate 
  with equally huge background rejection
The NA62 beamline

- SPS Protons @ 400 GeV steered to Beryllium target (T10)
- Secondary hadron beam – 6% Kaons (70% pions, rest = protons, electrons)
- 750 million particles per second, each momentum selected @ 75 GeV

- SPS capable of delivering enough $K^+$ in two years to perform NA62 physics

- **50Hz and 100Hz beam oscillation discovered with first NA62 data**
Kinematic rejection of background

- Before any selection is made, the single-track sample is dominated by the $K^+ \rightarrow \mu^+ \nu$, $K^+ \rightarrow \pi^+ \pi^0$ and $K^+ \rightarrow \pi^+ \pi^\mp \pi^+$ decays.

- These decays can be removed using the squared missing mass:

$$m_{miss}^2 \approx m_K^2 \left( 1 - \frac{|P_{\pi}|}{|P_K|} \right) + m_\pi^2 \left( 1 - \frac{|P_K|}{|P_\pi|} \right) - |P_K||P_\pi| \theta_{\pi K}^2$$
Kinematic rejection of background

\[
m^2_{\text{miss}} \approx m_K^2 \left(1 - \frac{|P_\pi|}{|P_K|}\right) + m_\pi^2 \left(1 - \frac{|P_K|}{|P_\pi|}\right) - |P_K||P_\pi|\theta_{\pi K}^2
\]

Need excellent momentum and position measurement of the $K^+$ and $\pi^+$ particles
Kinematic rejection of background

- Many processes contribute to the two signal regions!
Remaining backgrounds

- After kinematic selection, remaining backgrounds include:

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<td>20.7%</td>
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<tr>
<td>$\pi^+\pi^-\pi^+$</td>
<td>5.6%</td>
</tr>
<tr>
<td>$\pi^0e^+\nu$</td>
<td>5.1%</td>
</tr>
<tr>
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- Muon veto, $\pi$ and $\mu$ identification
- Photon veto
- Electron identification
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Muon veto, $\pi$ and $\mu$ identification
Photon veto
Electron identification
### Remaining backgrounds

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- Muon veto, $\pi$ and $\mu$ identification
- Photon veto
- Electron identification
There is a further background contribution from
1. Muons generated at the target
2. Muons generated by beam interactions with material,
3. Muons from decays of beam particles ($\pi^\pm \rightarrow \mu^\pm \nu$),

Creates a high-rate ‘halo’ of muons

The ‘halo muons’ are not correlated with Kaon decays in the fiducial volume.
Rejection based on Tagging Kaons, plus muon veto and $\pi - \mu$ identification
Expect $\sim 10^{13}$ $K^+$ decays in decay region in 2 years
Kaons are tagged with the CEDAR/KTAG system

CEDAR – collects Cherenkov light with fixed diaphragm

KTAG – 8-fold PMT array with $\sigma_t \approx 80$ ps

Kaon rate $\approx 45$ MHz

Rate of detected photons $\approx 4$ MHz per PMT
Kaons are tagged with the **CEDAR/KTAG** system
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- Kaon rate $\approx 45$ MHz
- Rate of detected photons $\approx 4$ MHz per PMT
**K⁺ measurement – GigaTracker**

- Position and momentum of $K^+$ measured with GTK
- **GTK** – beam spectrometer based on silicon pixel sensors
- Rate at GTK3 $\approx 750$ MHz, measures $\sigma_p/p \approx 0.2\%$, $\sigma_\theta \approx 16$ μrad, $\sigma_t \approx 200$ps

2015 data
**$K^+$ measurement – GigaTracker**

- Position and momentum of $K^+$ measured with GTK
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**Further improvements expected…**
• Position and momentum of $K^+$ measured with GTK
• GTK – beam spectrometer based on silicon pixel sensors
• Rate at GTK3 $\approx$ 750 MHz, measures $\sigma_p/p \approx 0.2\%$, $\sigma_\theta \approx 16$ µrad, $\sigma_t \approx 200$ps

• Further improvements expected...

---

2015 data without GTK

2015 data with GTK
**π⁺** measurement – STRAWS

- Position and momentum of **π⁺** measured by the STRAW spectrometer
- Straw tubes operated in vacuum – very low material budget!
- 4 chambers * 4 views (uv,xy) * 4 layers
- 112 straws per layer = 7168 total

\[ \sigma_{x,y} \leq 80\mu m \text{ per chamber} \]
\( \pi^+ \) measurement – STRAWS

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- ATLAS pixel resolution > 6 \( \mu m^2 \)
- LHCB VELO hit resolution > 5 \( \mu m^2 \)
π⁺ measurement – STRAWS

- Magnet system causes $\Delta p_x \approx 270$ MeV
- $\sigma_p/p \approx 0.32\% \oplus 0.008\% p \,[\text{GeV/c}]$
- $\sigma_{\theta(\kappa\pi)} \approx 20$-50 $\mu$rad
- $m^2_{\text{miss}}$ resolution $\approx 0.001$ GeV²/c⁴
\( \pi^+ \) measurement – STRAWS

- Magnet system causes \( \Delta p_x \approx 270 \text{ MeV} \)
- \( \sigma_{p/p} \approx 0.32\% \oplus 0.008\% \ p \text{ [GeV/c]} \)
- \( \sigma_{\theta(K\pi)} \approx 20-50 \mu\text{rad} \)
- \( \sigma_t \approx 6.5\text{ns track resolution} \)
- Not sufficient for \( K^+ \) matching
- \( \sigma_{t} \approx 80\text{ns hit resolution} \)
- Cannot be used in low-level trigger

\[ \frac{\sigma_{pT}}{pT} \approx 2-10\% \text{ ATLAS muons 2010} \]
\[ \frac{\sigma_p}{p} \approx 0.5\% \text{ LHCb muons 2015} \]

2014 data

Track time resolution: ~ 6.5 ns
STRAW tracker – 2015 data

\[ \mu^+ \nu \]
\[ \pi^0 \]
\[ \pi^+ \pi^- \]

Entries \ 8374604
Mean x \ 54.41
Mean y \ 0.003634
RMS x \ 20.14
RMS y \ 0.00236
Charged particle triggering – CHOD

- Charged Hodoscope (CHOD)
- Fast detector for triggering on charged particle(s)
- Time resolution $\sigma_t \approx 300\text{ps}$
- Each quadrant has 16 scintillating slabs. $16_x \times 16_y = 256$ intersections/quad

2014 data

2 planes (horizontal + vertical) of 64 plastic scintillator strips each

2014 data
Particle identification – RICH

- RICH – Ring Imaging Cherenkov detector
- Precise timing at < 100ps
- Over 2000 PMTs!
Particle identification – RICH

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Particle identification – RICH

- RICH – Ring Imaging Cherenkov detector
- Precise timing at < 100ps
- Over 2000 PMTs!

- Clear separation of $\pi$ and $\mu$ at low momentum
- Support RICH at high momentum with dedicated $\pi$ and $\mu$ particle identification

2015 data
Muon veto – MUV

- MUV system formed of two calorimeters (MUV1, MUV2) plus a segmented layer of plastic scintillator (MUV3)

- MUV1&MUV2 provide $10^{-5}$ muon rejection offline

- MUV3 provides muon rejection in the trigger
  MUV3 $\sigma_t \approx 450 \text{ ps}$, suitable for the low-level trigger

2014 data

Candidate time resolution: 450ps.
Photon veto – large angles

- The Large Angle Veto (LAV) – used lead glass blocks from OPAL
- Vetoes photons with $8.5 < \Theta < 50$ mrad, inefficiency < $10^{-5}$
- **12 LAV stations** distributed along the experiment
Photon veto – large angles

- The Large Angle Veto (LAV) – used lead glass blocks from OPAL
- Vetoes photons with $8.5 < \Theta < 50$ mrad, inefficiency $< 10^{-5}$
- **12 LAV stations** distributed along the experiment

**First Data:**

- $\sim 1$ns time resolution per single block

### 2014 data

<table>
<thead>
<tr>
<th>$\chi^2$ / ndf</th>
<th>269.7 / 65</th>
</tr>
</thead>
<tbody>
<tr>
<td>Constant</td>
<td>774.8 ± 6.9</td>
</tr>
<tr>
<td>Mean</td>
<td>-0.006916 ± 0.007069</td>
</tr>
<tr>
<td>Sigma</td>
<td>0.9567 ± 0.0048</td>
</tr>
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**$\delta\phi$ (rad) upstream cluster in LAV I**

- dPhi vs StDownstream for fixed upstream

**2014 data**

Station of downstream cluster
The Liquid Krypton Calorimeter (LKr, as used in NA48)

- Vetoes photons with $1 < \theta < 8.5$ mrad
- Also provides electron identification, and photon – electron separation
- High granularity: more than 13k cells of 2x2cm$^2$ area
- The **Liquid Krypton Calorimeter** (LKr, as used in NA48)
- Photon veto for photons with $1 < \Theta < 8.5$ mrad
- Also provides electron identification, and photon – electron separation
- High granularity (>13k channels)

**Photon Inefficiency ($E_\gamma > 10$ GeV) $< 8 \times 10^{-6}$**

$$\frac{\sigma_E}{E} = \frac{3.2\%}{\sqrt{E(\text{GeV})}} \oplus \frac{9\%}{E(\text{GeV})} \oplus 0.42\% \quad [\sigma_E/E \approx 1\% @ 10 \text{ GeV}]$$

$$\sigma_{x,y} = \frac{4.2\text{mm}}{\sqrt{E(\text{GeV})}} \oplus 0.6\text{mm} \quad [ = 1.5 \text{ mm @ 10 GeV}]$$

Comparable to CMS

**ATLAS barrel**

$$\frac{\sigma_E}{E} = \frac{10.1\%}{\sqrt{E}} \oplus 0.17\% \quad 3\% @ 10 \text{ GeV}$$
The Liquid Krypton Calorimeter (LKr, as used in NA48)

- Photon veto for photons with $1 < \theta < 8.5$ mrad, inefficiency $< 10^{-5}$
- Also provides electron identification, and photon – electron separation

![Graph showing MIPs, electrons, and hadrons with 2015 data, mean, and RMS values.]
Photon veto – medium angles

- The Liquid Krypton Calorimeter (LKr)
- For photons with $1 < \Theta < 8.5$ mrad, inefficiency $< 10^{-5}$
- Also provides electron identification, and photon – electron separation
- Analysis of the LKr data already underway
• Construction complete: Summer 2014
• Pilot physics run: October – December 2014
• First physics run: June – November 2015
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• Pilot physics run: October – December 2014
• First physics run: June – November 2015
The NA62 detector is designed to identify a single charged pion, produced simultaneously with a $K^+$ traversing the detector, in an otherwise empty event.

How much signal and background do we expect?

**Signal selection sketch:**
- $K-\pi$ association,
- $15 < P_\pi < 35$ GeV/c,
- Decay vertex in fiducial volume,
- No photon / muon / inelastic activity.

<table>
<thead>
<tr>
<th>Decay</th>
<th>Event/year</th>
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<tr>
<td>$\pi^+ \nu \bar{\nu}$</td>
<td>45</td>
</tr>
<tr>
<td><strong>Signal</strong></td>
<td>45</td>
</tr>
<tr>
<td>$\pi^+ \pi^0$</td>
<td>5</td>
</tr>
<tr>
<td>$\mu^+ \nu$</td>
<td>1</td>
</tr>
<tr>
<td>$\pi^+ \pi^+ \pi^-$</td>
<td>&lt; 1</td>
</tr>
<tr>
<td>$\pi^+ \pi^- e^+ \nu$, others 3 trk.</td>
<td>&lt; 1</td>
</tr>
<tr>
<td>$\pi^+ \pi^0 \gamma$(IB)</td>
<td>1.5</td>
</tr>
<tr>
<td>$\mu^+ \nu \gamma$(IB)</td>
<td>0.5</td>
</tr>
<tr>
<td>$\pi^0 e^+(\mu^+ \nu)$, others</td>
<td>neg.</td>
</tr>
<tr>
<td><strong>Background</strong></td>
<td>&lt; 10</td>
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The NA62 physics programme

• The NA62 detector is designed to identify a single charged pion, produced simultaneously with a $K^+$ traversing the detector, in an otherwise empty event.

• What other physics can be done with this experimental setup?
The NA62 detector is designed to identify a single charged pion, produced simultaneously with a $K^+$ traversing the detector, in an otherwise empty event.

What other physics can be done with this experimental setup?

1. Select muons: $K^+ \rightarrow \mu^+ \nu$ decays
2. Select electrons: $K^+ \rightarrow e^+ \nu$ decays
3. Select multi-track decays: LFV and LNV decays
4. Select $\pi^0$ decays: Dark matter search

Next few slides will show why these selections are interesting, using recent results from the NA62 and NA48/2 experiments.
1. $K^+ \rightarrow \mu^+ N_\mu @ \text{NA62}_{\text{RK}}$

- Search for long-lived neutrinos in $K^+ \rightarrow \mu^+ N_\mu$ decays
- A ‘bump hunt’ in the $K^+ \rightarrow \mu^+ \nu_\mu$ missing mass spectrum

\[ m_N \approx 275 \text{ MeV} \]
\[ m_N \approx 375 \text{ MeV} \]
2. $R_K @ NA62_{RK}$

- Value of $R_K$ can be precisely calculated in the SM

$$R_K^{SM} = \frac{\Gamma(K \rightarrow ev(\gamma_B))}{\Gamma(K \rightarrow \mu v(\gamma_B))} = \frac{m_e^2}{m_\mu^2} \left( \frac{m_K^2 - m_e^2}{m_K^2 - m_\mu^2} \right)^2 \left( 1 + \delta R_K^{EM} \right) = 2.477(1) \times 10^{-5}$$

- $R_K$ is sensitive to:
  - Ratio of mixing parameters of 4th neutrino $U_{e4}/U_{\mu4}$ at O(1) [JHEP 1302 (2013) 048]

- World’s most precise measurement of $R_K$ [PLB 719 (2013) 326]

$$R_K = 2.488(7)_{st}(7)_{sy} \times 10^{-5} = 2.488(10) \times 10^{-5}$$

0.4% precision

$$\Delta r_K = (4 \pm 4) \times 10^{-3}$$
3. $K^+ \rightarrow \mu^+ \mu^+ \pi^-$ @ NA48/2

- Search for $N_\mu$ in the mass range $240 \approx m_N \approx 400$ MeV using $K^+ \rightarrow \mu^+ \mu^+ \pi^-$ decays

- **World’s best limit** set by **NA48/2**: [PLB 697(2011)107]

\[ \mathcal{B}(K^\pm \rightarrow \pi^\mp \mu^\pm \mu^\pm) < 1.1 \times 10^{-9} \text{ @90\% CL} \]

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4. Dark Photon @ NA48/2

- The $\pi^0 \rightarrow \gamma ee$ decay can be mediated by a dark photon ($A'$, $U$)

- No excess in the data is found
- NA48/2 constraints exclude dark photon explanation of the $(g-2)_\mu$ discrepancy

- Recently published in PLB 746 (2015) 178-185
Triggering at NA62
The NA62 Trigger

• High particle flux of ~ 10 MHz demands a highly selective trigger

• The trigger is comprised of three stages:

  • **L0 Trigger:** Hardware (FPGA). Input rate: 10MHz, Output rate: 1MHz
    - Around 200kHz required for $K^+ \rightarrow \pi^+ \nu \nu$ trigger
    - Leaves 800kHz for (other studies + control channels)
    - ~ 400 kHz for exotic decay program
  
  • **L1 Trigger:** Software (Single detector). Output rate: ~100kHz
  
  • **L2 Trigger:** Software (Full information). Output rate: ~ few kHz

(Prospective numbers having assumed nominal intensity)
The proposed $K^+ \rightarrow \pi^+ \nu \nu$ trigger at L0

- The proposed L0 trigger scheme for $K^+ \rightarrow \pi^+ \nu \nu$ has four parts:

  1. A single charged particle:
     - At least three PMTs in the RICH
     - Coincident hits in a quadrant of the CHOD

  2. Consistent with a $\pi^+$ from $K^+ \rightarrow \pi^+ \nu \nu$:
     - Less than 40 GeV of ANY energy

  3. Veto photons:
     - Less than 20 GeV of EM energy
     - No signal in photon vetoes

  4. Veto muons:
     - No signal in MUV3
     - More than 1.5 GeV in the LKr OR more than 8 GeV of hadronic energy

- With rate of 200kHz, select $K^+ \rightarrow \pi^+ \nu \nu$ with 75% efficiency
  - 15% of signal loss is due to veto on ‘accidental coincidence’
The proposed ‘exotic decay’ trigger at L0

- Five L0 trigger lines are proposed for the rest of the physics programme
- These numbers assume 400 kHz L0 output rate with nominal beam intensity

- Single-track trigger (ST): \( \text{RICH}_1 \times \text{CHOD}_1 \) (downscale = 1000)
- Multi-track trigger (MT): \( \text{RICH}_2 \times \text{CHOD}_2 \) (downscale = 100)
- Dielectron trigger (2E): \( \text{RICH}_2 \times \text{CHOD}_2 \times \text{LKR}_{10} \) (downscale = 10)
- Dimuon trigger (2M): \( \text{RICH}_2 \times \text{CHOD}_2 \times \text{MUV}_2 \)
- Dilepton trigger (TME): \( \text{RICH}_2 \times \text{CHOD}_2 \times \text{MUV}_1 \times \text{LKR}_{10} \)
The NA62 trigger in 2015

- In 2015 ‘physics triggers’ were largely not used: beam time dedicated to TDAQ and detector commissioning
- Nevertheless about $10^{10}$ events have been recorded with minimum bias triggers
- These events can be used to “rediscover the Standard Model” as well as set more stringent constraints on heavy neutrino production
- Reconstruction and analysis of full 2015 data set already underway
Summary

• The NA62 experiment will study a variety of $K^+$ decays

• NA62 expects to collect 100 $K^+ \rightarrow \pi^+ \nu \nu$ decays in the next two years

• The “exotic decay” physics programme will set world beating constraints on new effects (LFV, LNV) and new particles ($N_\mu$)

• The NA62 experiment has begun operation

• Commissioning and analysis with 2015 data is proceeding

Watch this space!